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DISCUSSION OF PROCEEDINGS - SEPARATES

190, 276, 351, 357

HIGHWAY DIVISION

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Current discussion of papers sponsored by the Highway Division is presented as follows:

Number		Page
190	Analysis of Corrective Actions for Highway Landslides (Published in May, 1953. Discussion closed)	
	Krynine, D. P. and Woodward, Richard J.	1
	Baker, R. F. (Closure)	7
276	Highway Bridges on Deep Foundations (Published in September, 1953. Discussion closed)	
	Duclos, Louis (Closure)	11
351	Vertical Sand Drains for Stabilization of Muck-Peat Soils (Published in November, 1953. Discussion closed)	
	Raedschelders, H. M.	13
357	A Mathematical Examination of Spiraled Compound Curves (Published in November, 1953. Discussion closed)	
	Hickerson, T. F.	17
	Corrections	18

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The types of slides in a given region are influenced by the geology, topography, and climatic conditions of that region. To Mr. Baker's observations made in West Virginia the writers wish to add their observations made in California and in other localities where the aforementioned factors—and hence the slide types—differ, or may differ, from those mentioned by the author. In California—where a part of the year is rainless and the other part has much rain—the writers had a good opportunity to observe the contrasts in the stability of the same slope at different seasons and to understand clearly that excess moisture is a powerful contributing factor in producing slides. The writers have been enabled to study and correct slides affecting small properties, and they fully share Mr. Baker's opinion that, because corrective measures of landslides depend primarily on economics, expensive works in slide rehabilitation cannot be considered in these and similar cases.

Definition of a Slide.—A slide (or landslide) is a downward and outward movement of a portion of the soil (or soil-rock) mass with respect to that portion remaining in place. This movement is accompanied by a breaking of the bond connecting the separated and remaining portion of the mass. The separation is apparently preceded by more or less slow movements along the potential sliding surface followed by a more rapid movement of the separated portion.

Slides generally exhibit a characteristic topography. There is a typical area near the upper end of the slide from which the material has been carried away (excavation), and a part near the lower end in which the material has been deposited. The excavated part of the slide is usually bounded by a well defined continuous crack which is the exposed part of the sliding surface; this crack often has a parabolic shape both in the plan view and in the front elevation of the slide. The over-all shape of a slide is a closed curve which, however, is sometimes difficult to locate near the lower end of the slide. The closed curve bounding the slide generally has a confined "girt" as indicated in Fig. 8.

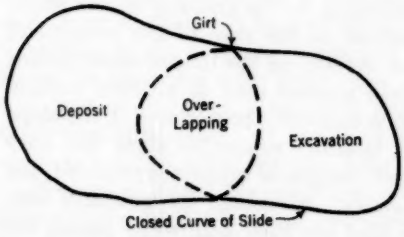


FIG. 8.—PLAN OF A SLIDE

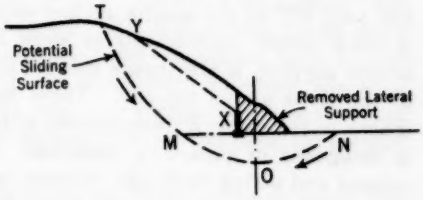


FIG. 9.—REMOVAL OF LATERAL SUPPORT

This girt approximately corresponds to the boundary between the excavation and the deposit.

Types of Slides.—Two basic types of slides are considered, deep slides and shallow slides. The essential difference between these two types of slides consists in the shape of the surface which bounds the separated part of the earth material from that remaining in place. Deep slides are bounded by curved slip surfaces resembling, in section, an arc of a circle. Shallow slides are bounded by slip surfaces which resemble a plane surface, rather than a regular curved surface.

Deep slides are formed by rotation about some center (Fig. 1), and the separated part of the soil or soil-rock material is a well-defined three-dimensional body. All failures of this type can be classified as being "in the soil" according to Mr. Baker. However, the writers have observed sliding surfaces passing through both the soil and the underlying soft shale.

Shallow slides which have been observed are of two types: (1) A slab slide occurs when a slab of earth material, approximately 5 ft thick, is separated from the rest of the earth mass by slip surfaces roughly parallel to the ground surface. Such slides, in front elevation, are also bounded by closed curves. Although similar in appearance to debris slides, slab slides are not always produced by the removal of the material at the toe. The slab slides often start from a crack at the top followed by a heaving at the toe of the slide. (2) A shallow "break-through" slide may be produced by the pushing action of the rising ground water as explained subsequently under the heading, "Upper Subsurface Water."

Both deep and shallow slides are produced in two steps: Part of the earth mass becomes separated from the main formation, and the earth mass moves downward and outward under the influence of gravity. The separation may be caused by (1) the increase in horizontal forces acting on the separated portion and a consequent increase in tangential stresses along the potential sliding surface; (2) a partial relief of the normal pressure acting on the potential sliding surface; and (3) a combination of these two factors. A change in physical properties of the mass, because of climatic factors, may also contribute to the occurrence of slides.

Removal of Lateral Support.—A relief, or more accurately, a weakening of the normal pressure acting on the potential sliding surface can be produced by the removal of the lateral support of the mass, as shown schematically in Fig. 9. In Fig. 9 the removed lateral support is shown by crosshatching. This removal is reflected in the general weakening of the normal pressure against the potential sliding surface TN and especially a decrease in tangential stresses along the part ON of the sliding surface contributing to the stability of the slope. Another factor contributing to slope failures, in the case of the removal of lateral support, is the tensile stresses that develop on the unsupported surface of the slope above the cut. These tensile stresses tend to produce vertical cracks in the slope, a phenomenon which is especially pronounced if the slope is composed of expansive materials. A laterally supported slope can only expand and shrink vertically whereas, when the lateral support is removed, the slope is free to expand and shrink laterally. Shrinkage in expansive soils causes forces which result in wide cracks that are filled with water during the

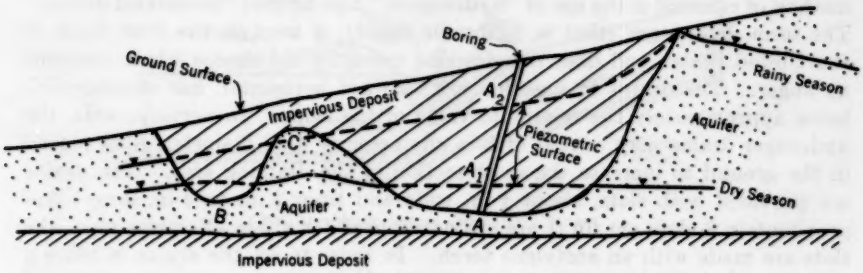


FIG. 10.—GROUND WATER UNDER PRESSURE

subsequent rainy season. This fact contributes to the decrease in shearing strength of the soil and subsequent slope failure.

Drainage as a corrective measure may or may not be helpful. It should be realized that the most efficient solution, in the case of the removal of lateral support, consists in constructing a retaining wall or flattening the slope. Both measures can be combined (dotted line XY in Fig. 9). In the general case, retaining walls are not too efficient in the rehabilitation of slides; however, the case of the removal of the lateral support is decidedly an exception. Addition of buttresses to the wall is helpful, but it is not always feasible because of lack of space.

Pore Pressure.—Another factor operative in the weakening of the normal pressure on the potential sliding surface is the pore pressure. Under the conditions shown in Fig. 10, the ground-water flow is constricted in the sandy aquifer below points A and B. If a boring is made to reach point A, water in the boring will rise to point A_1 in the dry season and to point A_2 in the rainy season. The loci of points A_1 and A_2 are piezometric surfaces in dry and rainy seasons, respectively. It can be concluded from Fig. 10 that during heavy rains the soil material at point A_2 is raised by a force equal to the distance from A to A_2 multiplied by the unit weight of water. Because of this force, the normal pressure on a potential sliding surface is decreased. Consequently, the shearing resistance of the soil material at point A_2 is decreased which may lead to a failure. If the impervious layer at point C is thin, the water in the underlying aquifer either will reach the ground surface by capillarity or will simply break through the impervious layer, thus causing a slide that should be classified as a shallow slide as mentioned under the heading, "Types of Slides." If an excessively deep excavation is made above point C, there is a probability that such an excavation will be periodically flooded. If a slide occurs above point C because of the breaking through of the thin impervious layer, such a slide should be corrected with great care. If not adequately corrected, the slide will recur at the same place when the corresponding piezometric surface has again risen sufficiently. In fact, such a slide has the same action on the ground water as a safety valve has on a boiler.

Removal of Excess Ground Water.—Slides caused by an excessive rise of the ground-water level should be corrected by removing the detrimental part of the ground-water flow—thus holding the piezometric surface. A common

method of removal is the use of "hydraugers," also termed "horizontal drains." The term, hydrauger (that is, hydraulic auger), is used on the west coast of the United States and does not describe correctly the device which contains no auger. The drains in question are also not horizontal, but sloping—5% being approximately the minimum value of the slope. In pervious soils, the hydrauger drains may consist of 2-in.-diameter or 4-in.-diameter pipes placed in the ground to increase the cross section of the draining area. The drains are provided with slots, about ¼ in. wide and from 2 in. to 3 in. long. Approximately 3 slots per lin ft are ordinarily used for a 2-in.-diameter pipe; the slots are made with an acetylene torch. In order to set the drains in place a slightly oversized hole is drilled by a machine which is a combination drill and wash borer. After the hole is drilled the drains are jacked into the hole, and the sections are welded together while the pipe is inserted. It is often convenient to place hydrauger drains in a fan-shaped arrangement with a common point of discharge.

In removing ground water from a stratified mass with impervious inclusions, it is often advisable, in conjunction with the hydraugers, to sink vertical holes (approximately 24 in. in diameter) to a convenient depth and to backfill the holes with crushed rock or gravel. In this arrangement one vertical well may be connected to each hydrauger. Rather than using hydraugers or trenches backfilled with rock or gravel, drainage is sometimes accomplished by sinking a row of vertical wells 30 in. in diameter, spaced approximately 7 ft on centers. Specially trained workers operating in the wells place drains by tunneling from hole to hole. Such an operation proves economical when substituted for short-drain trenches in remote places where the use of a trencher would be too expensive or where excessively long hydraugers would be required.

Increase in Tangential Stresses.—Placing a load (often a new embankment or fill) next to the top of a slope is another cause of deep slides. The failure in this case is the result of an over-all increase in tangential (shear) stresses along the potential sliding surface, although the normal pressure acting on that surface may not essentially change.

An effect similar to the placing of a load next to the top of a slope is caused by the removal of a load next to the toe of a slope (point N in Fig. 9). In New Haven, Conn., several buildings were erected on a slightly sloping street, close to each other. Demolition of one building in the row was causing continuous cracking of glass in the large windows of a building located several doors away. The cracking stopped when the demolished building was restored.

Correction of slides caused by the placement or removal of a load should be effected by removing or replacing the corresponding load.

Upper Subsurface Water.—Water in different stages (that is, hygroscopic, capillary, in the form of vapor, or locally condensed vapor retained between the particles) located above the water table, is termed "vadose" by the geologists. Perched water apparently is not included in this classification. When it rains continually during a long period, some of the rain water flows down the slope, and a part of the water is absorbed by the ground and moves downward. The upper soil layer, which has undergone a certain weathering process, is often rather pervious. This circumstance permits an easy downward

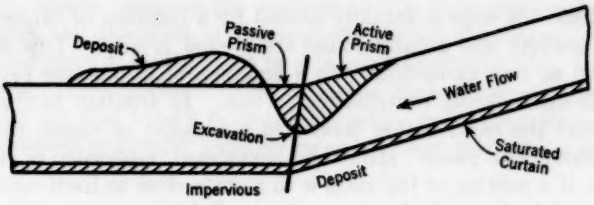


FIG. 11.—SLIDE AT THE BREAK OF A SLOPE

movement of the rain water to the underlying impervious layer. As soon as the few upper inches of the latter are saturated, a "curtain" preventing further downward penetration of the rain water is formed. The still-falling rain water is then forced to flow down the slope on top of this curtain until it fills the soil mass to the top. If there is sudden flattening (break) at any point of the slope—not necessarily at the foot of the slope—the lower part of the slope has less discharge capacity than the upper part. As water continues to collect in the steeper part of the slope, the impossibility of the further discharge through the vertical plane separating the upper and the lower parts of the break will be resolved either by pushing out a portion of the earth mass (crosshatched in Fig. 11) thus producing a slide, or forming a swamp condition at the break. The presence of the break is favorable, but it is not a compulsory condition for slides of this type.

Slide scars on natural slopes may be observed in abundance in regions of young geology. The cause of these slides is apparently the intrinsic instability of the slopes that tend to reach stable equilibrium. In some places the slide scars are so abundant that they really should be considered as characteristic landforms of the region.

Efficient rehabilitation of the slides caused by the upper subsurface water is difficult. In hilly regions with extensive slopes, water should be prevented from reaching the places where it could be detrimental, so far as the formation of slides is concerned. It is advisable to stop water as close as possible to the source or at least as high as possible on the slope, although no general statement can be made for this case. Hydraugers may be used to stop the water, but they are not fully efficient following initial installation. In a given condition, a combination of hydraugers with rock-filled drains or other drainage features should be considered.

Slab Sliding.—Slides produced by the sliding of huge earth slabs on an almost frictionless surface often located at a depth of approximately 5 ft can be termed slab slides. These slides occur during continuous rainstorm periods and often are caused by agencies similar to those causing deep slides, such as the placing of a fill or the removal of the lateral support. A fill not placed next to the top of the slope, but somewhere at the middle of this slope, may cause a shallow slab slide of large magnitude. This fact suggests that additional loads on the area such as a building with shallow footings, may increase the weight of the slab and push it down. It should be realized that the foregoing statement requires considerable verification. Slab sliding is generally corrected by proper drainage.

Slide Causes.—A slide is actually caused by a complex of causes in which the force of gravity and ground water are always present. Dry slides have been reported as rare exceptions. In a complex of causes one cause is predominant, all others being contributing factors. In addition to the predominant cause and the contributing factors in a complex of causes leading to a slide, the "immediate cause" should be considered, especially in legal cases. For example, if a portion of the mass is in a state close to limit equilibrium—that is, if its safety factor is close to unity—a slight increase in either the load or the intensity of the rainfall may cause a slide, thus being the immediate cause of the slide. The immediate cause should be sharply distinguished from the real cause of the slide.

Mr. Baker is quite correct in stating (under the heading, "Fundamental Considerations") that

> "Of great importance is the fact that by eliminating or by modifying the effect of any one of the causes the stability [of the slope] will increase."

The writers would suggest the substitution of the words "contributing factors" for "causes" in this statement. Since the detrimental action of ground water is always a contributing factor to the production of a slide, it is easy to understand that drainage represents "a sound approach to a slide correction." It is known, however, that looking for the cause of the slide is essential. In fact, if the slide has been caused by a load placed at the top of the slide, a drainage solution will not be sufficient. With regard to legal cases (and these are many), the engineering expert has to give to the court a clear answer as to the cause of the slide.

Creep.—The writers were most interested in the mechanics of creep movement as presented in Fig. 4. This type of earth movement has been insufficiently studied, and the explanation of creep by the presence of various potential slip surfaces within the creeping mass is perhaps an ingenious guess. It is believed that, since the creeping mass (as shown in Fig. 4) is reposing on a firm sloping base and slowly moves down, it should be in the state of unstable equilibrium alternated with microscopic translation. If this is so, the creep should be caused by very small oscillations of the center of gravity of the whole mass caused by readjustment of its constituents. It is probable that changes in moisture content are responsible for these readjustments.

In addition to the classical example of creep (Fig. 4) there are movements that lie somewhere between sliding and creeping. The following phenomenon is cited as an example. In a shallow valley (near Oakland, Calif.) with a clayey floor and a longitudinal slope along the thalweg of approximately 20%, a well-defined slide 500-ft long was produced with a regular crack and a "shelf" at the top. The following year, in bulldozing the locality, the toe of the slide was undermined. The slide moved bodily approximately 1 ft and continued moving slowly for a period of at least three months, during which there was no rainfall.

Mr. Baker's advice to refer the creep and flow cases to an authority in this field is good, provided such an authority exists.

Surveying a Slide.—Surveying existing slides and searching for potential ones is greatly facilitated by the use of aerial photographs. This source of

information clearly discloses the features of the slide area—even those that have escaped the attention of the engineer during the survey. The cost of aerial photography is not as great as it is often believed.

Conclusion.—Mr. Baker's activities in the theoretical and practical study of landslides are well known to engineers active in this particular field. The paper constitutes additional valuable information in this field of endeavor.

R. F. BAKER,[18] M. ASCE.—The comments of Messrs. Krynine and Woodward are particularly helpful as their experience with landslide problems, particularly in the western part of the United States, have suggested factors that are also true in West Virginia. Many of the ideas contained in the paper might not apply throughout the United States, but the discussion indicates that many of the principles are the same.

[18] Engr. of Soil Mechanics, State Rd. Comm., Charleston, W. Va.

Of particular interest is the differentiation offered by Messrs. Krynine and Woodward between "shallow" slides and "deep" slides. Their approach is a realistic one, particularly when applied to the investigation of corrective measures. In fact, it is probable that many of the suggested methods for treatments of landslides could be divided on the basis of their applicability to deep or shallow movements. In West Virginia the practice has been to estimate the depth of the overburden in the manner suggested, and the technique has been found to be helpful.

The writer was also interested in the comments concerning failures in underlying shale formations. Only one such failure has been observed in West Virginia, and this was a case in which extremely heavy blasting operations were involved. Other such failures in the Appalachian Plateau province have been reported in Pennsylvania. Failures in consolidated sediments are not considered to be average conditions, however, as a failure in the shale implies that the shearing resistance of the soil is greater than that of the shale, or that the two resistances are essentially equal.

In 1947 a theory was suggested[13] by Mr. Buckingham that a landslide analysis based on $\phi = 0°$ was a valid approach. Several of the ideas expressed by Messrs. Krynine and Woodward would indicate that such an assumption can not be warranted as a generality. Specifically, the statement is made that the loss of lateral support near the toe of a slope results in a reduction of the shearing resistance. In addition, general acceptability of horizontal drainage is implied. Neither of these ideas could be valid for an analysis based on $\phi = 0°$. The writer does not know whether Messrs. Krynine and Woodward intended such an implication, but such an interpretation would verify observations of slides in West Virginia. The discussion concerning the use of horizontal drainage is particularly important as the western states have long used this technique. For the area within the Applachian Plateau very little use has been made of this method. The first application of the method in West Virginia was completed in the summer of 1953.

[13] Discussion by E. M. Buckingham of "Landslide Investigation and Correction," by Hyde Forbes, *Transactions*, ASCE, Vol. 112, 1947, p. 435.

The principle of horizontal drilling changes the entire concept of landslide correction as an effective installation can be accomplished at a minimum cost. It is felt that drainage as a corrective measure has been overemphasized; in West Virginia, drainage methods have not been economical for many of the slide conditions. However, use of horizontal drainage does permit a much wider application of drainage corrections.

It has been found that general statements concerning the application of specific types of corrective measures to certain types of landslide causes are not valid. Two such generalities were mentioned by Messrs. Krynine and Woodward. One (under the heading, "Increase in Tangential Stresses") is that "Correction of slides caused by the placement or removal of a load should be effected by removing or replacing the corresponding load." Although there is no question of the validity of the principle, the approach would not work often enough in West Virginia for such a generality to be made. The use of a retaining wall is not always valid where there has been a loss of lateral support unless very shallow slides or quantities are involved. The statement by Messrs. Krynine and Woodward may be based on conditions of extremely stable slopes prior to the loss of lateral support. Under such conditions, replacement of the loss with a mass of approximately the same resistance should lead to the same stability as existed prior to the excavations. However, for deep ancient slides near the point of limiting equilibrium, retaining devices to replace the loss of lateral support have not been found to be successful in West Virginia.

Perhaps the most significant part of the discussion was concerned with the legal aspects of landslides. There is little in the literature concerning this important division of landslide work. Although the writer's experience does not correspond completely with that of Messrs. Krynine and Woodward, the intelligent appraisal of "cause" and "contributing factor" is most essential. The one cause and several contributing factors do not always constitute the "complex of causes." The writer does accept the words "contributing factor" for "cause" as a valuable change. Perhaps the disagreement is not that one cause predominates, but that it is practically impossible to ascertain which is the predominate cause, and what is the exact effect of the contributing factors.

One of the principal difficulties in relying on the designation of a "predominant cause" can be illustrated by the following. If it is assumed that an excavation has resulted due to a loss of lateral support, but that heavy seepage also exists beneath the surface of the ground, both factors should be recognized immediately as "contributing factors." If one states that the excavation is the "predominant cause," could not the slide have occurred without the presence of water? If, however, the water is the predominant cause, would the slide have occurred without the excavation? Certainly the removal of the lateral support must be partly at fault, regardless of other conditions. If some peculiar conditions such as a leaking water main or reservoir or extremely adverse climatic conditions had led to extreme seepage conditions, the situation would be changed. Many such conditions can arise, and the statement that either cause is the predominant one can lead to an impasse. Landslides have

been rare about which a dogmatic statement can be made as to the predominant cause with the exclusion of other specific factors.

In the legal phases of landslide work, the writer has been in the position of either (1) defending an action specified as leading to damage, or (2) condemning an action as having damaged the client. For the first condition the most certain escape from a claim appears to be in proving that the action could not have been even a contributing factor. If the action has been a contributor to the movement, then the difficult task is to prove some other contributor has a greater influence and would undoubtedly have produced the failure even without the minor help of the action defended. The second type of claim is generally less difficult, for the major step is to prove that the action was a contributor. Quite often this is evident as being true or untrue, and the client can be so advised. Of course, if a major contributing factor exists, one must estimate whether the action in question could have accelerated the movement.

A helpful concept to the writer in dealing with the legal aspect of landslides is the geomorphology principle mentioned by Messrs. Krynine and Woodward. In the paper, the idea was expressed that the soil mass is inevitably headed for the topographic bottom of the area. If the action in question has assisted in accelerating or increasing the motion under consideration, some degree of contributancy appears to be involved. If an action has contributed to the movement, the action is most difficult to defend. In fact, if the action is a contributor to movement, a degree of liability will automatically exist in many cases. The extent of the liability then becomes debatable and may often be decided satisfactorily with a quantitative approach based on the principles of soil mechanics.

DISCUSSION OF HIGHWAY BRIDGES ON DEEP FOUNDATIONS
PROCEEDINGS-SEPARATE NO. 276

LOUIS DUCLOS,[1] M. ASCE. — The writer finds no point of controversy in Mr. Walker's discussion, and finds it impracticable to present further expository material. Hence, no further comment will be added.

1. Head Bridge Designer, State Dept. of Highways, Baton Rouge, La.

DISCUSSION OF VERTICAL SAND DRAINS FOR STABILIZATION OF MUCK-PEAT SOILS PROCEEDINGS-SEPARATE NO. 351

H.M. Raedschelders, U.I.Lv. — After reading the article of Messrs J. C. Carpenter and E. S. Barber, I thought it would be of interest to give some information about the use of vertical sand drains for stabilization of muck-peat soils in Europe. In the "low-lands" all along the north-west coast of Europe engineers often had to build embankments for roads and railways, on very soft alluvial soils. Among the traditional methods of treatment, the willow mattresses were widely used. When the construction of concrete roads required a firm foundation and settlement after construction of pavement had to be avoided, new methods were sought. In the north of Germany displacement of the soft material has been obtained by blasting. Charges of explosives buried in the soft soil under the center of the embankment material pushed the muck-peat soils laterally away, till the embankment material was supported by the compact substratum. The acceleration of consolidation by means of vertical sand drains was adopted for the first time in Germany when a new road had to be built on glacial deposits in Schleswig-Holstein. Here 1017 drains were installed, aggregating 20.604 lineal feet. The vertical holes were constructed by the rotary jetting method. The result was very successful. The description can be found in an article by Dr. Alfred Dücker in "Strassen- und Tiefbau, Strassenbau und Strassenbaustoffe, Heft 10/1950."

In Belgium the first application of vertical sand drains was on a portion of the highway from Brussels to Ostend (the London-Istamboul way) (1952). The soil survey made by the Geotechnical Institute, showed an alluvial deposit, about 33 feet deep, of an actual little brooklet. The height of the fill was about 30 feet. Normal settlement due to consolidation, computed by Terzaghi's hydrodynamic theory of consolidation is shown by the curve (1) (fig. 1). In order to increase the rate of settlement the sand-drainage system was adopted. 1034 drains, with a center to center spacing of 10 feet were used in a hexagonal array. The vertical columns of sand 16 inches in diameter and ranging in depth from 12 to 34 feet (total length 23.784 lineal feet) were covered by a 3 feet thick sand blanket.

For the construction and backfilling of the vertical holes the driven mandrel-method has been used and no difficulties were encountered. Instead of the concrete point to close the lower end of the steel pipe, as described in the paper of Messrs Carpenter and Barber, we used a plug of sand and gravel compacted at the bottom of the open casing by a few firm blows of the driving hammer. The hitting of that plug by the special hammer was sufficient to drive the entire casing into the ground through the very soft alluvial clay. After reaching the permeable

1. Director of the National Geotechnical Institute of Belgium.

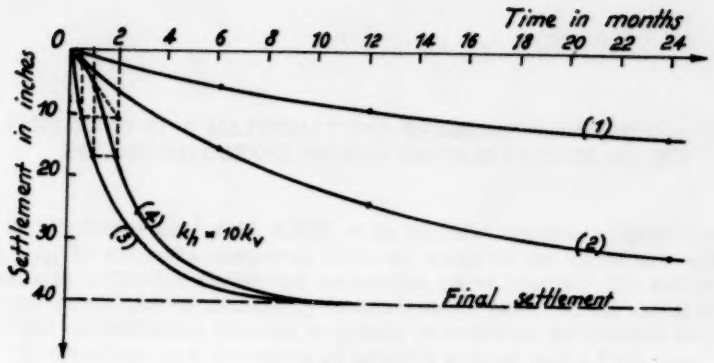
substratum, a few blows of the tamper with at the same time a pulling up of the casing delivered the plug. The vertical sand drain was formed by gradually filling the casing during its lifting. This method saves the cost of the concrete point and produces at the same time a very permeable lower-end at the sand-column. The sand for the drains and blanket had a coefficient of permeability of 0.28 ft per day, compacted at a porosity of 40%. This permeability was thought to be sufficient and at the same time the sand was fine enough to prevent the intrusion of the surrounding soil, the last condition being of more importance in this case.

The three-dimensional process of consolidation also computed by means of the theory of consolidation of Terzaghi, is represented by the curve (2) (fig. 1). The computation was made on the assumption that the bed of clay and peat is hydraulically isotropic. But since every sedimentary bed of clay is far more permeable in a horizontal direction than in a vertical direction, the filter wells were also computed assuming that $k_h = 10\ k_v$. The corresponding time-consolidation curve (3) is also shown on fig. 1. (4) shows the graphical constructed time-consolidation curve, by gradual application of the surcharge pressure.

The described project being the first application of vertical sand drains in Belgium, special arrangements had been taken to check the progress of consolidation during and after construction of the embankment. Settlement plates cause too much difficulty for the proper compaction of the fill material, so use was made of settlement cells for the measuring. The cell operates on the principle that the level of liquids in two vessels connected by a tube will be the same. One of the two vessels consists of a small chamber welded to a square steel plate 12 in. on each side, placed in the embankment on the sand blanket. The chamber contains two orifices, connected with a reinforced rubber hose to 1 inch diameter steel tubes. Water is poured into one of the tubes until it overflows the upper orifice of the chamber and flows our by the other tube. The level of the water in a connected glass gage, next to the inlet tube, is the same as the upper orifice in the buried cell and can be during and after construction of the embankment Fig. 2 shows the results of measurements on settlement cells. Cell N° one had been placed on top of the sand blanket, in the center of the embankment. Cells N°S 2 and 3 were installed near the toes of the embankment. The dashed part of the curves had been found before construction of the embankment and was due to the weight of the sand blanket and the action of the mandrel driving.

Comparison of the observed curve (1) (fig. 2) and computed curve (4) (fig. 1) proves the validity of the assumptions made in the design.

A new project, using 3273 vertical sand drains, aggregating 93.435 lineal feet, is under construction near to Brussels on the location of the highway Brussels-Melsbroek airport.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8
10
12
14
16
18
20
22
24
Settlement in inches
10
20
30
40
(1)
(2)
(3)
(4)
$k_h = 10k_v$
Final settlement

Fig. 1

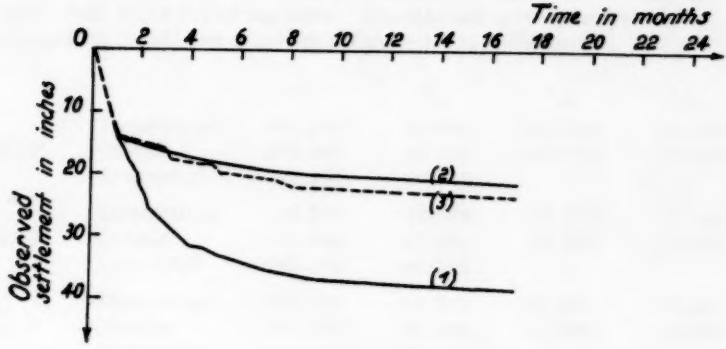
Time in months
0
2
4
6
8
10
12
14
16
18
20
22
24
Observed settlement in inches
10
20
30
40
(2)
(3)
(1)

Fig. 2

DISCUSSION OF A MATHEMATICAL EXAMINATION OF SPIRALED COMPOUND CURVES PROCEEDINGS-SEPARATE NO. 357

T. F. Hickerson,[1] A.M. ASCE. — In the field layout of a spiral connecting the arcs of a compound curve all points on the spiral are established by deflection angles and successive chord lengths. The end point of the spiral may be checked by measurements based on the radial shift "p" but the deflection location is usually accepted as the correct one.

To determine how the spiral as actually laid out in the field compares with the theoretical spiral, the coordinates of the midpoints (x_m, y_m) and endpoints x_1, y_1) of the spirals of the four examples were computed by traverse along the chords. Chord slopes were computed from deflection angles and chord lengths. A constant chord length equal to the true chord for an arc on the osculating circle at point A (Fig. 1 and 2) of $L_s/10$ was used. These coordinates are compared with the theoretical coordinates and with those obtained by using the radial shift in the following table. Coordinates were computed to thousandths to add one significant figure to the differences.

		x_1	y_1	x_m	y_m
	Theoretical	292.332	56.808	149.220	13.055
Ex. 1	Chords	292.339	56.824	149.222	13.055
	Arcs-shift	292.387	56.822		
	Theoretical	192.376	45.569	99.285	10.143
Ex. 2	Chords	192.386	45.596	99.287	10.144
	Arcs-shift	192.481	45.595		
	Theoretical	290.166	67.005	148.537	18.239
Ex. 3	Chords	290.160	66.989	148.534	18.238
	Arcs-shift	290.220	67.016		
	Theoretical	570.161	163.541	295.680	44.191
Ex. 4	Chords	570.153	163.489	295.672	44.188
	Arcs-shift	570.269	163.554		

A study of the table shows that all discrepancies are well within the usual survey precision, justifying present practice in spiral layouts. Moreover the discrepancies may be accounted for in various ways. The deflection angles used to compute chord coordinates were those given in standard tables (corrected for osculating circle deflections) which may be in error by as much as three seconds in the given examples. Also, the chord lengths should vary with the degree of the osculating circle along the length of the spiral.

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Insofar as the coordinates determined using the radial shift are concerned, a larger source of error lies in the assumption that the length of each of the circular arcs is equal to $L_s/2$. This assumption fixes Δ_1 and Δ_2 and in effect further assumes that points B and B_1 (Fig. 1 and 2) lie on a line parallel to 0_1C. B_1 is the end point of the theoretical spiral. That such is not the case may be demonstrated by considering Formula 8 or 20. These formulas are based on solution-by-traverse, $\Sigma Y = 0$. If the equivalent formulas for $\Sigma X = 0$ are solved for "p", completely different values are obtained.

A theoretically exact value of "p" may be obtained by using both Σx and Σy equations, the unknowns being Δ_1 or Δ_2 and p. To illustrate, the equations for Case II are

$$\Sigma x = 0 = R_1 \sin \Delta - x_1 - (R_1 - R_2 - p) \sin \Delta_2 \qquad (r)$$

$$\Sigma y = 0 = (R_1 - R_2 - p) \cos \Delta_2 + R_2 - y_1 - R_1 \cos \Delta \qquad (s)$$

Combining to eliminate p

$$\tan \Delta_2 = \frac{R_1 \sin \Delta - x_1}{R_1 \cos \Delta + y_1 - R_2} \qquad (t)$$

In Example 4, $\Delta = 30^{\circ}$, $x_1 = 570.161$, $y_1 = 163.541$, $R_1 = 1432.395$, and $R_2 = 954.930$. Solving, $\Delta_2 = 18^{\circ}\ 00'\ 47''$ and p = 5.217 as compared with the nominal value of 5.232 and a value of 4.995 using Formula 20 with Δ_1 and Δ_2 fixed.

This paper is a valuable contribution to spiral theory because it validates the theory of the osculating circle and shows that current practice in spiral layout is well within tolerable limits. It also demonstrates that there is no need for computing tables based on the formulas developed in the paper.